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ENGINEERING PROBLEMS IN U.S. TIDAL WATERWAYS

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ENGINEERING PROBLEMS IN U. S. TIDAL WATERWAYS

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SYNOPSIS

The large increase in waterway commerce and vessel size in recent years has made it necessary to improve most of the coastal harbors in the United States by enlarging, deepening, or, in some cases, confining natural waterway channels to meet the navigation requirements. Many inter-related factors, common in tidal waterways but foreign to river or channel flow free of tidal influences, contribute toward complexities in the functional planning, design and maintenance of tidal waterways for which sound basic theories have not been developed; hence judgment, based on past experience, must be relied upon for solutions to many of the related engineering problems.

Engineering problems in tidal areas of interest to navigation may be divided into three general classifications: (1) Those relative to shoaling of inlet and bar channels where tidal and littoral currents, littoral drift and wave action affect rate and location of shoaling; (2) those relative to shoaling of interior channels, slips, turning basins, and other navigation facilities where movement and deposition of material are controlled primarily by tidal currents; and (3) those relative to hydraulic phenomena, such as tidal elevations and ranges, current velocities and directions, salinity intrusion, surges, etc.

The influencing factors are listed and those concerning surges in harbors, salt-water intrusion and shoaling are discussed in detail. Problems encountered in the design of four major component parts of tidal waterway improvements; namely, bar channels, jetties, interior channels and breakwaters, are reviewed, and general statements of possible solutions are presented. Tidal waterway maintenance, particularly with regard to dredging, is described briefly, and the need for provision of sufficient maintenance funds is stressed. Some tidal-waterway problems are illustrated by discussions of the improvements at the mouth of the Mississippi River, Grays Harbor and the mouth of the Columbia River.

INTRODUCTION

Navigation of tidal waterways dates back many centuries to the days when the Phoenicians plied the seven seas, but it is only within the last 100 years that man has made major improvements to the natural waterways of the world. With the development of navigation and the continuous increase in the size and draft of vessels it became necessary to provide protection to waterway entrances and harbor areas by the construction of jetties and breakwaters and to dredge deeper and wider navigation channels.

Obviously, definite knowledge of reliable relationships between the tidal regimen and the physical characteristics of the tidal waterway became

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essential, particularly for determining in advance the effects of any planned major operation on the waterway. Also, such knowledge was needed in connection with planning of regulatory works and dredging operations with a view of maintaining navigation project depths in shoaling reaches of tidal waterways. It was soon discovered by costly experience that in designing regulatory works for local improvement in a given reach of an estuary, the possible adverse effects in other sections of the waterway system must not be overlooked.

A large percentage of the civil works projects in the United States assigned to the Corps of Engineers involves the improvement of tidal waterways, which are inevitably costly, but can be much less so if there are sufficient data to prevent expensive errors in engineering design.

Factors Affecting Tidal Waterways

Tidal phenomena occurring in any waterway seldom result from a single cause; rather they are a more or less complex interaction of a number of factors. Therefore, if a change in the regimen of a waterway is desired in order to effect an improvement, the change in each contributing factor and in the resulting interaction must be determined. The principal factors to be taken into consideration in the solution of problems of construction and maintenance of tidal waterways are: (1) Tides, (2) surges in harbors, (3) fresh-water discharge, (4) salt-water intrusion, (5) waves and currents, (6) littoral drift, (7) fresh-water sediments, (8) characteristics of waterway bed and banks, (9) shoaling characteristics, (10) navigation channel characteristics and (11) navigation requirements.

The conditions producing the tide at the mouth of a waterway are well understood and general information on the behavior of ocean water in its advance and retreat in tidal waterways is available, but, as is evidenced by the several controversial tidal theories, laws describing the interactions of all the factors involved have not been established which can be used with reasonable confidence to predict the magnitude of tides, currents and surges in a proposed new tidal waterway, or to determine in advance the effect of major physical changes in the tidal regimen. While the subjects of littoral drift, channel shoaling and saltwater intrusion have been and are being extensively investigated at some localities, sufficient comprehensive studies have not been completed to formulate design methods and procedures for general application. Therefore, in most cases, it is found necessary to conduct extended investigations to determine the effects of those factors on project plans. Although navigation requirements regarding channel dimensions and alignment are well established, mainly as a result of experience of pilots in handling ships through tidal waterways, generalized design criteria have not been established for navigation channel appurtenances, such as dikes, jetties, etc. which are constructed to maintain navigation channels by preventing or reducing shoaling, and here again, detailed studies, including model tests, are required in the development of project plans for those appurtenant structures.

Examples of related factors to be considered in designing tidal waterway improvements are that: (1) future changes in channel dimensions and alignments will produce changes in flow conditions which may materially affect navigation and maintenance, (2) distances to which salt water moves upstream in a tidal channel may be so altered by project changes that industries or irrigation projects using river water would be seriously damaged or made ineffectual, and (3) construction of a breakwater to protect certain docking areas

of a waterway or of jetties to prevent shoaling in one area may so alter wave patterns and tidal currents that equally undesirable shore erosion or shoaling conditions may develop in other areas of the waterway.

Three of the factors listed above; namely, surges in harbors, salt-water intrusion and shoaling, are selected for more detailed discussion. These three factors produce some of the most interesting and important engineering and economic problems in tidal waterways.

Surges in Harbors

Surges are of importance in the design and construction of harbor facilities, since these disturbances affect floating objects within the confines of the harbor. The most striking example has been in connection with the mooring of ships to piers, for, even when restrained by heavy tackle, moored ships have been subjected to drift amplitudes of up to 10 feet, snapping mooring lines, breaking piles, and damaging the ships themselves. It has been fairly well established that in practically all cases surges in harbors result from long-period wave trains arriving from the open sea, one clearly recognized source of such waves being seismic disturbances, which frequently occur in the Alaskan region of the Pacific Ocean.

The problem in designing harbors subject to surges is to locate mooring facilities in areas of minimum vertical motion, usually areas in which surge amplitudes are a minimum as a result of refractive and diffractive effects. Since these effects are determined by the configuration of the reflecting boundaries, the harbor shape will have an important bearing on the dampening effect on waves and water motion within the basin. Thus, in a typical design study it may be necessary to consider the effects of a number of possible development plans, each of which imply a change in the basin dampening capacity. As the factors that determine the dampening capacity of a harbor with various proposed improvement plans are difficult to evaluate by analytical methods, model studies should be conducted to minimize surge motion and to define optimum areas within the harbor for specified types of operational activity.

Salt-Water Intrusion

Among the many hydraulic phenomena which involve density currents, the one relating to the intrusion of saline waters from a sea into a river or an estuary is of prime significance to coastal engineering. Other problems which are encountered include: (1) The effect of releasing salt water from a navigation lock into the fresh water of a navigation canal, (2) the effect of intrusion of salt water from a canal into a fresh-water lake, and (3) the effect of constructing sills or other works to curb salt-water intrusion. Flow characteristics in the salt intrusion phenomena, involving the mechanism of interfacial resistance, the individuality of the moving saline wave fronts, velocity distribution in vertical sections, the criteria of interfacial mixing and the mixing in the fresh water above the saline wedge are not well understood. Although model testing is obviously a reliable approach to the understanding of some of the problems, model laws for density current phenomena are not well established.

In agricultural areas lying adjacent to tidal waterways the interest is in the extent of the salt-water intrusion, because the inland flow contains damaging amounts of salt, which requires that lands be drained and provisions made to restrict contamination of the underground fresh-water, if the lands

are to remain productive. Another important practical problem is the contamination of industrial and domestic water supplies along tidal waterways, as in the lower reaches of the Mississippi River where one of the principal objections to the presence of salt water in the river is pollution of the water supply at New Orleans. The intrusion of salt water from the Gulf of Mexico is in the form of a wedge having a fairly well defined interface which moves upstream through the Mississippi Passes under the fresh water. Last year, 1953, during extremely low fresh-water flow in the river, the upper end of the salt-water wedge reached a maximum distance of 170 miles upstream from the Gulf, or 47 miles above the city limits of New Orleans.

As a contribution to the study of salt-water intrusion, the Corps of Engineers, U. S. Army, has initiated and is supporting various studies on this subject, which are being carried out by the Committee on Tidal Hydraulics, the Waterways Experiment Station and the National Hydraulic Laboratory of the Bureau of Standards. These studies should add considerably to the knowledge of the mechanics of density flows and model laws for salt-water intrusion.

Shoaling in Tidal Waterways

The most wide-spread and costly problem is the matter of shoaling in navigation channels. The prevention of shoaling, thereby maintaining navigation depths, requires either constant maintenance dredging or the construction of costly training works in many of our important waterways.

The principal natural sources of the material causing shoaling in tidal waterways are: (1) The watershed area from which fresh-water runoff reaches the tidal section; (2) caving banks and eroding stream beds in the rivers leading to the tidal section; (3) marsh areas from which marsh streams discharge into the tidal section; and (4) the ocean area adjacent to the mouth of the river. Shoaling of improved channels may also result from improper deposit of dredge spoil, and redistribution of bottom material lying outside of the navigation channel by wave action, cross currents, and other such forces. In some localities fine, dry material is blown by winds into the waterway from beaches and similar areas. And it is thought by some that under certain conditions soft material may reach adjacent channels after being squeezed from under spoil banks.

The Shoaling material in navigation channels of tidal waterways which have large river inflows, such as the Columbia River Estuary, is almost entirely sand of various gradations. On the other hand, in tidal waterways which have large tidal prisms compared to the fresh-water inflow, such as the Delaware River and San Francisco Bay, the shoal material is usually referred to as mud. Some of this mud first reaches the tidal section as suspended matter, containing considerable colloidal material, in the fresh-water flow. Upon contact with the salt water, flocculation begins, and, as the material travels downstream in the ebb flow, the process proceeds at various rates, depending on conditions of temperature, salinity, turbulence, etc. until the flocs attain a specific gravity or other condition which causes them to sink to the bottom. They are then moved about under the varying current conditions until a location favorable for deposit is reached.

In the upper reaches of the tidal section of a river or estuary, the fluvial characteristics predominate over the tidal, and the knowledge of transport of water-borne material in non-tidal streams may be found largely applicable. In the lower reaches of the section, however, tidal influences usually control; therefore, material movement and other shoaling processes do not follow the pattern for non-tidal streams, especially where the water-borne material is

predominately that carried in suspension. The movement of material in a tidal waterway leading to the formation of a shoal is not the simple process of a single deposit of material in a given location but the end result of a complicated series of pickups and deposits, of movements to and fro.

One aspect of the shoaling problem that merits more attention is that it is often preponderantly due to extreme rather than average conditions. Material deposited in a shoal by currents resulting from normal flows may be removed by higher velocities and a further increase in these velocities may induce scour and movement of the material to another locality, whereas material deposited by less frequent high velocities is unlikely to be removed by lower velocities. A channel that remains open during normal conditions may be virtually filled during a single severe storm or freshet with suspended or bed-load material carried by the high velocities. This is probably the reason that formulas and plans developed in the light of mean tidal ranges, mean fresh-water flows, and other more usual conditions have often failed in their application.

Another aspect is that shoaling is predominately governed by conditions at or near the bottom of the waterway which may explain why improvements planned from the results of surface or mid-depth float or current-meter observations have failed. This emphasizes the need for more complete knowledge of the characteristics of the salt-water wedge, the flow conditions around it during its advance and retreat, its effect on newly deposited sediment and that still in suspension, as well as the need for a more extensive use of that knowledge in planning improvements.

A further fact to be considered is that an improvement which eliminates shoaling in one area will very probably cause or increase shoaling in some other area and if the new area is elsewhere in the navigation channel, the improvement will be to some extent self defeating unless additional counteracting measures are taken. In some instances it is possible to perfect plans of improvement which will provide adequate bottom velocities to keep the shoaling material in motion and eventually pass it entirely through the waterway.

Planning and Design of Tidal Waterway Improvements

Too frequently in the past, waterway improvements have been built without benefit of comprehensive planning and design, and as a result many structures have failed for lack of strength to withstand the forces to which they are subjected, while others have been overbuilt to such an extent as to be wasteful of public and private funds. As a basis for functional planning and design, the factors previously discussed should be considered, if pertinent, for each locality. Then analyses of the factors involved together with determination of possible construction methods and availability of materials usually will suggest several alternative methods of improvement. In selecting the best plan, preliminary plans for all of the methods believed capable of producing the desired end result should be prepared and compared economically. In addition, the effects beyond the limits of the problem area must be evaluated in terms of public interest and with a view to possible liability. Four major structures or parts of tidal waterway improvements; namely, bar channels, jetties, interior channels and breakwaters are discussed herein.

The Bar Channel

The bar or shoal area lying off the mouth of a tidal inlet is an accumulation of sediment fed by littoral drift moving along the adjoining coastal shore,

augmented in some cases by sediment from upstream sources. The bar is traversed by one or more natural channels maintained by tidal flow, the largest of which is nearly always the path of the principal ebb current. Continuing encroachment of littoral sediment causes bar channels to shoal and to migrate, so that natural bar channels are seldom suitable for navigation requirements.

In the location and design of an improved bar channel, the volume and current pattern of tidal and fresh-water flow in the inlet; the characteristics of sediment discharge; the direction and location of the travel of littoral drift; the direction, strength and frequency of waves which threaten the safety of vessels; the location of the natural depths between the mouth of the waterway and deep water in the ocean; the dimensions and alignment required for prospective navigation under the most adverse navigation conditions; and the character and use made of coastal shores on each side of the inlet all must be considered. In selecting the alignment of a bar channel to be improved by dredging, an analysis of wave refraction in the channel region and diffraction effects of structures considered will aid in determining the most suitable location. If the most suitable alignment from the standpoint of wave exposure results in increased initial dredging to provide the bar channel, the benefits to be gained must be weighed against the increased cost. The position of the bar channel at the time the improvement is being planned must not be taken as a governing factor in channel alignment without first studying historic migratory behavior of the channel.

Since the greatest deterioration of a bar channel is caused by moving sand, the design location should be such as to reduce this to a minimum by orienting the axis perpendicular to the largest storm waves, if possible, to lessen sand movement and to allow scouring action of the tidal currents the best opportunity to hold the channel in place. As severe storms may approach the bar channel from one of several directions, it is necessary to determine which one predominates because the wave direction will usually not vary much from that of the winds, but if the angle of difference is appreciable, a compromise location will be necessary.

Consideration should always be given to the feasibility and economy of maintaining a bar channel by dredging alone, and the relative merit of that method compared with the employment of training works before decision is made as to the most suitable plan of improvement or maintenance.

Bar Channel Training Works, Jetties

The principal function of bar channel training works or jetties is to stabilize and deepen the navigation channel through the deposits of fine material at the mouth of a river or entrance to a bay by preventing littoral sediment and/or stream-borne sediment from depositing in the channel, confining the discharge area to promote scour and extending farther into deep water the point where currents slacken and transported material is deposited. Jetties at the entrances to a bay or river also protect the navigation channel from storm waves and cross currents, and sometimes from deposits of materials which are moved alongshore by wave action.

The functional design of jetties involves determinations of optimum relations between number, alignment, spacing and length to meet the needs for protection against wave action, shoaling and shore erosion, as well as the requirements of navigation. A single jetty on the updrift side of the channel will usually suffice if reversals in drift direction are minor and if stream-borne sediments are not important. However, it is now generally conceded that where control of velocities is required to prevent shoaling by stream-borne

sediments, or where littoral drift is not strongly predominant in one direction, double jetties are necessary.

Jetties are most often aligned parallel with the selected channel although converging or "arrowhead" jetty alignment has been employed in certain cases; but this is usually more costly, less effective in controlling velocities, and advisable only where a constricted entrance or interior spending beaches are necessary to control wave action. Jetty spacing is governed first by navigation requirements and second by the channel cross-section area necessary to maintain velocities sufficient to prevent excessive shoaling. The latter value will vary with the character of sediment involved and with the tidal and fresh-water regimen.

A rule of thumb formula for cross-sectional area between jetties, derived from naturally maintained gorge dimensions at several unimproved inlets on the Pacific Coast of the United States, is: Cross-sectional area of gorge below mean sea level, in square feet, equals volume of tidal prism, in acre feet. Another formula, first proposed by M. P. O'Brien, for determination of area of a tidal inlet is as follows:

$$A = 1000 T^{0.85}$$

where A is the cross-sectional area of the inlet, in square feet, and T is the volume of tidal prism, in square mile-feet.

Jetty lengths are governed by the channel project depth and the littoral characteristics of the coastal shore. A jetty on the updrift side of an inlet will impound material in the form of accretion along the adjoining updrift shore and its effective life as a littoral barrier depends upon this impounding capacity. It is thus necessary to predict the rate and manner of littoral accretion in selecting the optimum economic jetty length, which is established on the basis of the effective life of the structure for impounding and dependent also upon the amount of channel maintenance which can be accomplished more economically by dredging rather than extending the jetty out farther into deep water.

The downdrift shore adjacent to a jettied inlet may be expected to erode at approximately the same rate as accretion occurs on the updrift shore, except when a substantial part of the bar is on the downdrift side of the jettied channel nourishment of the shore defers erosion until the bar material is depleted. Damaging erosion effects must be carefully predicted and evaluated in the economic analysis of bar channel training works. Where the value of prospective erosion damage is high, it will be advisable to consider methods of bypassing littoral drift across the inlet in lieu of or in addition to training works, or to provide equivalent periodic nourishment of the downdrift shore with material from other sources.

The selection of the exact site, availability of materials and method of jetty construction presents economic problems. As the cost of transporting materials to the site is generally a large percentage of the total cost, a thorough search is required to locate the nearest source of suitable materials. When alternative sites will accomplish substantially the desired purpose, that which requires the least distance for transportation of materials and/or permits the most effective construction method should be selected.

Interior Channels

Planning and design of interior channels within tidal waterways are based on the operational characteristics of ships, taking into account not only the

requirements of present-day vessels but also those of prospective construction. The trend in vessel design generally is toward larger and faster craft; for example, tankers are now being built to 30,000 dead-weight tons, 625 feet long, 85 feet wide and drawing 34 feet loaded in salt water.

In open water a navigator has considerable latitude in which to make adjustments to offset the external forces acting on his ship, but in the interior channel of a tidal waterway time and space are limited. The unstable forces of tide, current and wind must be judged and compensated for quickly and accurately to avoid mishap and the navigator must be ever alert to possible interference from other traffic. The straighter, deeper and wider the channel, the easier it is to navigate and maintain economic speed.

The channel depth must prove adequate clearance under keel, with proper allowances being made for sinkage and wave action. Sinking results from the vessel dropping with the level of the supporting water surface in the vicinity of the vessel which is caused by the increase in velocity of water as it flows around the moving vessel. Additional lowering of the ship occurs when it drops into the trough of a large wave. In exposed channels this latter item is an important consideration and several additional feet of channel depth may be required to secure an all-weather channel.

Although width has some effect on sinkage, the major problem of navigators in restricted channel is one of ship control and is most pronounced when ships pass each other and when they navigate bends. Passing ships develop asymmetrical pressures on the two sides of each ship which tend to sheer the ship from its original course, while in navigating a bend a ship forms a tangent to the curvature of the bend, and, consequently, is positioned slightly off center so that rudder action is necessary to prevent development of sheer. Widening of channel bends is in general use to minimize these hazards.

In shallow or restricted channels the ship power required increases tremendously in comparison to that for equivalent speeds obtained in deep water, so with maritime interests becoming more economy minded because of the increased cost of ship operation, there is strong pressure for larger channels and particularly channels with greater clearance under keel so that open deep-water operating efficiency can be approached in restricted channels.

Interior channels which are improved for navigation in tidal waterways fall into two general classes; namely, those in which construction of the required channel modifies to a large degree the regimen of the waterway, and those in which the channel to be constructed makes comparatively little change in existing hydraulic conditions.

In the improvement of the first class, the location should be such as to avoid cross currents, the training works should make the channel as straight as possible, and necessary bends should be of easy curvature. If practicable, such improvement works should be located and constructed so as to provide a gradual enlargement of the channel from its upper end to the mouth.

Longitudinal walls or dikes are the most effective means of training tidal waterways of the first class, especially when the bed and banks are composed of soft material. Where a section of the waterway is wider than the trained channel, so that considerable reduction in its width results, a system of spur dikes should be built first with the outer end of the dikes at the edge of the proposed channel, which will produce deeper water in the desired location for the new channel and filling between the dikes. If the deepened channel does not attain the regularity in alignment, depth and width desired, the heads of the dikes may then be joined by longitudinal walls to correct for much of the undesirable irregularity. Where the channel runs through marsh or other soft

ground, it may be desirable to stabilize the bends, which may be accomplished by providing walls or revetment, whichever is more advantageous.

In the second class of interior channel, the basic problem is the determination of cross-sectional areas necessary for maintenance of the given channel depth, without undue maintenance dredging. In tidal waterways along the North Pacific Coast this is accomplished by a simple method which is essentially as follows: From hydrographic survey charts the width between banks is scaled at as many sections as can be found where proposed project depths exist. These are the sections produced by tidal currents, stream flow and the other factors which have operated over a long period of time. The between-bank widths are then plotted against the distance along the waterway, and from the smooth curve drawn through the points the proper width of channel can be determined from any point. Where widths are too small and depths are excessive, as often occurs in the gorge section of the entrance to a waterway from the sea, the natural cross-sectional area will furnish a guide in estimating the width corresponding to project depth which will be self-maintaining between control works at the entrance, due allowance being made for possible reduction in hydraulic efficiency.

The use of such a design procedure may often eliminate the need for velocity measurements, determinations of tidal prisms, estimates of velocities needed for maintenance, consideration of materials, silt and bed-load measurements, effects of salt water intrusion and river floods, etc. as the channel produced by the river over a long period of years gives, in such cases, a complete answer by integrating the effects of all factors involved. Thus, the engineer's problem is reduced to reproducing self-maintaining sections of desired depths by constructing control works, which should be permeable, in some cases, so as not to disturb the regimen of the waterway, and in all cases over contraction must be avoided to minimize erosion problems. New channel depths should, in general, be created by dredging, and dependence for maintenance placed in the control works.

Breakwaters

A breakwater, as the name implies, is a structural impediment to destructive forces of storm waves which renders an area safe for the mooring, operating and handling of ships and small craft. They are constructed (1) to create artificial harbors; (2) to render secure and usable natural harbors that are enclosed and protected, except from one, usually least damaging, direction; (3) to convert open roadsteads into protected harbors; (4) to protect areas within the interior of large, established harbors against wave action originating within the harbor; and (5) to provide protected mooring basins for fishing and pleasure boats.

Among the problems affecting design of breakwaters are the physical characteristics of the site and factors such as exposure to wind, waves, current and tides; forces resulting from waves tend to damage or destroy any such structures, and tidal or littoral currents may cause scour and undercutting. If possible, data relative to the characteristics of storm waves at the locality should be determined by direct observation. Direction and velocity of prevailing winds and tidal and river currents, the angle at which waves break on the beach, material in the shore and bottom at the site, and silt carrying capacity of nearby streams all cause variations in the effect of the structure.

If serious beach erosion appears possible, the effect which the proposed works will have on the adjacent shore line should be investigated, caution being used in arriving at conclusions as to sand movement along the beach for

to err in this may defeat the purpose of the breakwater. Because of a mistake as to the direction of sand movement, one breakwater built to keep sand out of a small boat basin, instead locked the sand in the basin, preventing its escape, with resulting shoaling of the basin.

The cost of construction is often the controlling factor in determining the type of breakwater to use, and considerable savings in transportation cost can be made if suitable materials in required quantities are available locally. In general, a limited number of types of construction will be practical in any locality; but the cost of constructing and maintaining the different types may vary considerably, and the final decision as to the type may be dictated either by the initial cost of the structure or the annual cost of maintenance.

Maintenance Problems in Tidal Waterways

Federal maintenance work in tidal waterways, as authorized in the laws adopting river and harbor projects, may be classed under two main categories: (1) Repairs to harbor jetties, breakwaters and channel stabilization works; and (2) dredging to maintain project dimensions in navigation channels and anchorages of coastal harbors and waterways. While many engineering problems are encountered in the two classes of maintenance work, particularly in the field of dredging, the problem of funds for necessary maintenance work is perhaps the most perplexing.

Insufficient Maintenance Funds

Funds appropriated in recent years for maintenance work have not been sufficient to provide for full maintenance of our important waterways, nor are there adequate amounts requested in current federal budget estimates. As a result, maintenance work must be limited to the most urgent projects necessary in the interest of military and essential domestic requirements, while work is postponed on other waterways, where shipping is made possible only at reduced draft or by placing reliance on the range of tide to permit cargoes to be delivered.

The past necessity for partial or no maintenance in some areas, because of lack of funds, is revealed in the poor condition of many jetties, breakwaters and other protective structures. On the Pacific Coast, for example, some structures now need almost complete replacement instead of repairs of a minor nature, a most uneconomic policy in that complete reconstruction of structures is much more costly than recurrent repair, and structure benefits are partially or wholly lost during the period when there is need of extensive repair. Limited maintenance of channel regulating works is particularly applicable to the Passes of the Mississippi River where a considerable amount of repair work on the dikes and jetties is desirable to provide a more stable channel, thereby decreasing the annual dredging requirements of this important passageway to the ports and harbors on the inland waterway systems of the Mississippi River and its tributaries.

Partial maintenance dredging of channels also is uneconomic and a serious impediment to the free flow of commerce, as a result of vessels scraping the bottom. Turbulent propeller wash on the sides of a restricted channel will cause a higher rate of shoaling with resultant damage to vessels and the frequency of maintenance operations also is increased thereby, which directly affects the cost of maintenance over a period of years.

Provision of adequate funds for maintenance requirements is especially urgent in view of the large volume of commerce being moved on our improved

waterways and harbors. Statistics for the calendar year 1952 reveal that the harbors and waterways of the United States carried 887,250,000 tons of water-borne commerce, which represents a continuation of the high level of activity experienced in recent years. In view of the unsettled international situation, our waterways should be placed in condition to alleviate to the fullest extent possible any transportation emergency.

Maintenance Dredging

Shoaling occurs to some extent in every tidal waterway, and it is most serious in those through which navigation channels have been dredged appreciably deeper than channel depths existing under natural conditions. The Delaware River alone requires maintenance dredging which averages about 13,000,000 cubic yards annually, costing in the order of \$2,500,000. Similarly, Savannah Harbor, Charleston Harbor, Mississippi River, Houston Ship Channel and Columbia River Estuary approximate \$1,000,000 annually for each. The Beach Erosion Board has compiled figures that indicate an average annual rate of maintenance in waterways under the jurisdiction of the Corps of Engineers of 185,000,000 cubic yards, costing on the order of \$20,000,000, and, in addition, an annual cost for all governmental agencies and private interests in U. S. tidal waterways was estimated to total about \$48,000,000.

The important engineering problem in this category concerns means of reducing the enormous volume of shoal material being dredged annually. Examination of current dredging methods reveals at least three practices which, it is believed, contribute to excessive volumes of maintenance dredging: (1) removal of low-density shoal materials, called "fluff," from navigation channels; (2) spoiling dredged material in adjacent water areas, marshes and offshore areas along the waterway; and (3) agitation dredging of shoal material.

In some waterways, particularly along the Atlantic Coast, shoal materials consist of fine clay and flocculated particles which increase in density from that of sea water to a dense mud over a thickness of 5 to 10 feet. When an echo-sounder is used to determine the location of the channel bottom, two bottoms are indicated; one at the fluff line and the other at the firm bottom, so that, if dredging is accomplished on the basis of the fluff line several feet depth of shoal material is dredged which is semi-liquid and only slightly more viscous than sea water. It is questionable whether passage of vessels through this material has any major adverse effects on vessel movements, such as loss of speed due to increased ship resistance, loss of maneuverability, or loss of operating efficiency due to plugging of condensers.

In order to reduce the volume of semi-liquid or fluff material being dredged, current practice in some waterways is to make check soundings with a lead line and base dredging operations on a hypothetical bottom several feet below the fluff line. Another method is to establish the bottom at a constant density level of 1100 grams per liter by sampling, thus leaving the fluff material of lighter density in the waterway. An investigation has been initiated by the Corps of Engineers to evaluate the effects of vessel passage through fluff material of various densities in hope of establishing the optimum density required for satisfactory vessel movement. This investigation includes tests on a large tanker, loaded to several drafts, passing through shoal areas of the Delaware River. If it is found that vessel movement is not affected seriously by passage through several feet of shoal material with higher densities, say up to 1200 grams per liter, further reductions can be made in annual maintenance dredging.

The practice of spoiling dredge material into adjacent deepwater areas, marshes and offshore areas has in many cases been accomplished improperly, and a large percentage of the material finds its way back into navigation channels. When spoil is deposited in deep-water areas adjacent to a navigation channel, often the material does not remain in place, as is evidenced by the fact that the deep areas continue to redevelop, and it is suspected that a large percentage of the spoil material is carried back into the navigation channel by tidal currents and wave action.

The most common practice, in which a large annual yardage is involved, is to pump into the marshes adjacent to navigation channels. Although marsh grasses tend to trap coarse material, dredge flow and later rains, wave action and tidal currents eventually transport most of the fine material back into the navigation channel, where it again forms shoals. Spoiling in offshore areas to be effective must be diked to prevent "runback" of large quantities of material into the waterway, since measurements of runback from undiked offshore spoil areas along the Savannah River and Charleston waterways indicated that as high as 97 per cent of the material previously pumped was returned, consequently requiring continuous dredging.

Another practice which results in rehandling of large volumes of shoal material is the so-called agitation dredging, which is done with a hopper dredge during the ebb tide period when there is a good outgoing current. After the hoppers are filled, the dredge continues to pump, discharging the shoal material through the overflow onto the surface of the waterway from which sand fractions quickly settle to the bottom, but the fine silt remains in suspension for some time and, consequently, is carried a considerable distance downstream or out to sea, depending on how near the mouth of the river the dredging is done. In some cases, only a small percentage of the agitated material reaches the sea. Instead, it settles in water areas adjacent to the navigation channel and is later carried by tidal currents and wave action back into the channel, or, after being carried part way to sea on the ebb tide, is returned upstream by the following flood tide with the net result that, while agitation dredging temporarily restores channel depths in localized reaches, much of the material soon returns in one location or another. The obvious solution is, of course, either to carry the shoal material mechanically to sea or pump it into diked areas.

Illustrative Tidal Waterway Projects

In the foregoing sections of this paper, the engineering problems in U. S. tidal waterways have been discussed in general terms. In this section, three tidal waterways; namely, Mississippi River (Mouth to New Orleans), Grays Harbor, and Columbia River at the mouth, will be described to illustrate conditions under which previously mentioned problems occur and the complexities when several of the problems are interrelated in a single waterway.

Mississippi River (Mouth to New Orleans)

New Orleans, one of the major ports of the United States for ocean going ships, is located on the Mississippi River 95 miles upstream of the Head of Passes and from there to deep water in the Gulf of Mexico is 22 miles via Southwest Pass and 15 miles via South Pass, which are the two main approaches to the Mississippi River (Figure 1). The following navigation channels have been authorized for the waterway: Southwest Pass, 40 ft. by 800 ft; South Pass, 30 ft. by 450 ft; and Mississippi River from Head of Passes to

New Orleans, 40 ft. by 1000 ft. Bar channels of 40 ft. by 600 ft. and 30 ft. by 600 ft. are maintained at the entrances to Southwest and South Passes, respectively.

The plan considered most feasible for carrying out the adopted improvement consists of the following: Dredging in the Mississippi River proper, dredging in both South and Southwest Passes, dredging through the bars at the foot of each pass, regulation and contraction works at the Head of Passes and in the passes, and regulation and control of outlets downstream of New Orleans. Discussion of the problems involved will be limited to those encountered in Southwest Pass.

The combination of poor alignment and hydraulic inefficiency of the channels at the Head of Passes causes a decrease in velocity and shoaling at the entrance to Southwest Pass (Figure 2). The solution of this problem might appear to consist of some realignment of the banks of all three passes in this vicinity and part of the main river upstream toward Cubits Gap and contraction of the entrance to Southwest Pass to approximately a 1400-foot surface width, which has proven to be the most efficient width throughout the remainder of the Pass. This contraction could be obtained by a system of timber pile training works and dikes.

An alternative solution is constant maintenance dredging. During the period 1942-47, a 35-foot entrance channel was maintained by dredging an average of 680,000 cubic yards annually, and it is estimated that maintenance of the 40-foot channel would involve annual dredging of about twice that figure. The cost estimate of annual maintenance of the 40-foot channel by dredging is not considered excessive in comparison with the estimated annual cost of constructing and maintaining contraction works together with a minimum of maintenance dredging. Accordingly, the channel at the entrance to Southwest Pass is being maintained by dredging only.

Approximately three miles downstream of the Head of Passes the channel decreases in width from an average of 1750 feet to an average of 1450 feet, which is the governing width established by the dikes in the lower reaches of the Pass. Material moved from the bar at the head of Southwest Pass tends to be deposited in the wider reach, due to the lower velocities, and forms a shoal along the west bank of the pass. While these shoals are not of great volume, their removal causes additional expense and the inconvenience of the diversion of dredging plant from more important maintenance work, so that their elimination by contraction works in the form of permeable pile dikes is justifiable.

The reach of Southwest Pass from between miles 10.5 and 19.5 was contracted to a surface width of 1450 feet by permeable pile dikes which were completed in 1939, and dredging for channel alignment and depths was completed in 1943. Since that date, shoaling has occurred, particularly during and after floods of greater than average magnitude, which has caused deficiencies in channel width and depth, requiring corrective dredging to maintain channel dimensions. Experience indicates, however, that the regimen of the channel remains fairly stable during low and normal river flows and that the training works effectively reduce the annual maintenance dredging in this reach of the pass.

In the lower three miles of Southwest Pass, which is confined by earth jetties, pile training works and permeable dikes, high water shoaling is caused by the sudden reduction in velocity at the end of the jetty channel. Lack of maintenance during the war years resulted in subsidence of the jetties considerably below project grade, permitting large flows to pass over,

thereby reducing the velocity in the jetty channel and causing additional shoaling. The jetties are now being kept to grade and permeable dikes are being screened to increase the velocity and thus reduce shoaling. As the shoal area progresses onward into deep water, the jetties will need to be lengthened to maintain non-shoaling velocities.

Shoaling in the entrance to the jetty channel also results from the littoral current which flows around the end of the east jetty, causing a large eddy and a resulting slackening of velocity at the critical area where the river and littoral currents meet, at which point the most serious shoaling tends to form. It is proposed to construct a semi-permeable dike, 800 feet in length, outward from the end of the east jetty to deflect the littoral current away from the jetty entrance and while it is probable that shoaling would occur along the channel side of this dike it would be far enough removed from the channel to prevent any injurious effects.

Another way to reduce shoaling at the several problem areas in Southwest Pass is to increase the discharge at the expense of Pass a Loutre. Various obstructions and contraction works have been tried at the Head of Passes, since the start of improvement of Southwest Pass in 1908, but not one of these works has had any effect on the distribution of flow, which indicates perhaps that the discharge capacity is a function of slope and hydraulic efficiency rather than of any localized minor obstruction. It seems unlikely that the discharge of the pass can be increased without some major change, as closure of some of the main distributaries of Pass a Loutre, the results of which would be extensive and unpredictable. This kind of plan should not be attempted without prior model investigations.

Grays Harbor

Grays Harbor is a tidal estuary on the southwest coast of the State of Washington, its entrance from the Pacific Ocean lying about 45 miles north of the Columbia River mouth. The harbor is roughly pear-shaped, diverging from the Chehalis River at Aberdeen, 15 miles east of the entrance, to a total width of 13 miles, including North and South Bays. The entrance from the Pacific Ocean is formed by two narrow sandy peninsulas, the northerly one, 7 miles long, and the southerly one, 4 miles long, terminating at Point Brown and Point Chehalis, respectively. Westhaven Cove, a small craft harbor, is situated in the bight formed by the eastward curvature of the latter point (Figure 3).

Two rubble mound jetties, constructed under Federal authority, converge seaward constricting the waterway width from 9,000 feet at the points to 6,500 feet at the outer entrance. Beyond the jetties, an ocean bar composed of fine gray sand lies convex to the sea with a minimum depth of 20 feet. A ship channel from deep water extends in a northeasterly direction across the south end of the bar to a point just west of the south jetty, continuing within the entrance eastward along the south jetty for about two miles, and then veering northeastward to bypass Point Chehalis and join the North and South channels leading to Chehalis River at Aberdeen. Dimensions of the ship channel under Federal project requirements are 30 by 600 feet to North Channel, where the width is reduced to 350 feet.

The coastal area in the vicinity of Grays Harbor is subject to severe storms, particularly during winter months. Recent studies of harbor conditions made in connection with development of the existing project indicate that waves within Grays Harbor affecting the entrance to Westhaven Cove can attain heights of 5 to 6 feet, and swells most directly affecting the jetties and

Point Chehalis are from the west and northwest, attaining heights of 20 feet.

As a result of the severe wave action and the normal tidal action within the harbor, extensive erosion has occurred along the north and west shores of Point Chehalis, which, if not counteracted, would eventually obliterate Point Chehalis and Westhaven Cove. Erosion also occurs along the north side of South Jetty of which approximately 5000 feet of the outer end has been destroyed. Protection of the small boat harbor in Westhaven Cove against wave action and maintenance of the ship channel by dredging, at the rate of 1,500,000 cubic yards annually, are two of the functions necessary in coping with the problems in this area. Uncertainties as to the relative importance of wave action and tidal currents makes any choice of an over-all protection plan difficult; consequently, a program has been initiated by the Corps of Engineers calling for model studies, field measurements and other investigations, with only such remedial construction as was immediately required but which might be utilized in an over-all plan.

A fixed-bed hydraulic model, reproducing all of Grays Harbor and the entrance area, was constructed and tested at the Waterways Experiment Station from 1950 to 1952. The principal results and conclusions indicated by the model studies are summarized, as follows: (1) Training dikes or other structures for deflecting tidal currents away from South Jetty and Point Chehalis would be generally ineffective unless so extensive as to become excessive in cost or to develop objectionable conditions for the navigation channel; (2) realignment of navigation channels would have no effect on tidal currents, and therefore erosion; (3) continued destruction of the outer end of South Jetty tends to reduce flood-tide velocities around Point Chehalis thereby alleviating the scour problem; (4) the reduced length of South Jetty does not appear to cause any shoaling of the entrance channel; (5) dumping of dredged material northwest of Point Chehalis might result in appreciable sand feeding on the north and west shores of Point Chehalis; (6) groins, constructed along the north shore of Point Chehalis, would reduce tidal currents along that shore and induced eddies would produce accretion if wave action were not too strong; (7) construction of three short breakwaters at the entrance to Westhaven Cove would result in adequate protection of the small boat harbor and currents would be beneficial from the viewpoint both of navigation and maintenance.

In accordance with the findings of the model tests, protective works were constructed progressively as the actual needs were established by prototype behavior. These initially consisted of four permeable woodpile groins along the north shore of Point Chehalis and breakwaters A and B at the entrance to Westhaven Cove, but, after one year of operation, it was found that the permeable groins did not arrest the erosion as wave action continued to erode the shore (Figure 4). It was concluded that rock reinforcement should be added to the groins to render them sand tight and three additional rock groins should be constructed seaward of the first four. Since erosion of the north shore continued during the next year, rock revetment and construction of a gap in groin No. 5, to permit continuous nourishment of the north shore, was required to maintain the shore line.

Proposed future construction will consist of a Breakwater C to protect a proposed extension of the small boat harbor to the southeast; rock revetment along the west side of the harbor, if and when erosion of the west shore endangers the harbor; and reconstruction of the outer end of South Jetty, if and when its continuing destruction results in severe shoaling of the bar channel or otherwise produces undesirable navigation conditions. At the present time, there appears to be no feasible way to reduce or eliminate shoaling in the navigation channels which would be less costly than maintenance by dredging.

Columbia River at the Mouth

The Columbia River enters the Pacific Ocean at the Washington-Oregon boundary between two low sand spits, Peacock Spit on the north and Clatsop Spit on the South, which are connected by a submerged sandbar a short distance seaward of the river entrance (Figure 5). Baker Bay is a large shallow water area partially separated from Columbia River to its south by Sand Island. The existing Federal Project for Columbia River provides for a channel at the mouth 40 feet deep and not less than one-half mile wide secured by dredging and jetties, supplemented by groins. The project channel crosses the ocean bar and extends into the river mouth for a distance of 3 miles from the seaward ends of the north and south jetties, which are constructed principally of rubble stone, 2 1/2 and 7 miles long, respectively.

Maintenance work has included dredging along Clatsop Spit, where sand deposits encroach northward on the established channel alignment; provision of spur jetty A inside the north jetty to offset the cutting action of currents, which tend to move the channel northward in that vicinity; and protective works including pile dikes on the south side of Sand Island.

Improvement of the navigation channel has not kept pace with the growth of commerce and increase in size and draft of ships in recent years. Rough seas at this location cause large vessels to pitch as much as 15 feet below their normal keel elevations in smooth water, so that passage of vessels with drafts exceeding 25 feet is hazardous during storm periods, and they must await favorable seas to enter or leave the waterway. These vessels have also experienced difficulty in making the relatively great deflection in sailing direction at the outer ends of the entrance jetties, where sands have encroached on the south side of the channel, and the actual sailing line has been too close to the north jetty for safety during storms from the south.

Shipping interests using this port urge improvement of the hazardous conditions by deepening the channel to 48 feet at mean lower low water for a minimum width of one half mile, located in conformity with the range lights established for the existing project channel, which would permit full loading of the ships and lessen delays in sailing. Two plans have been considered for providing the desired improvements: Plan 1 contemplates initial excavation and subsequent maintenance of the channel by dredging without additional structural works; whereas, under Plan 2, dredging would be supplemented by construction of a spur jetty B about 5,500 feet long located between north jetty and jetty A.

The two major unknowns in these plans are: (1) The amount of dredging that will be required to maintain a 48-foot channel without jetty B, and (2) the reduction in maintenance dredging that would result if jetty B were constructed. It is certain that under plan 1 maintenance dredging will be increased over that required for the existing 40-foot channel, but whether the increase will be small or several times the present amount is purely speculative. Likewise, the effect of jetty B on reduction of maintenance dredging is uncertain.

Presumably, construction of jetty B would effectively reduce sand encroachment at the westerly end of Clatsop Spit to aid in maintaining a channel depth of 48 feet; however, there is valid indication that construction of jetty B might cause a shifting of the problem area to the west, with only temporary improvement in shoaling conditions, and might also result in a considerable loss of the deflective effect of north jetty, in which case the areas between the three jetties on the north shore would shoal materially and the main flow of the Columbia River would take a more westerly direction seaward. Clatsop

Spit would then extend seaward, depositing large quantities of sand in the navigation channel and causing the bar channel to shift to a more westerly direction. If, ultimately, Clatsop Spit should extend westward as far as the end of north jetty, flow would be fan-like over the bar, probably requiring increased dredging to maintain a 48-foot channel.

After full consideration of the many factors, it was concluded that plan 1 should be adopted for the initial improvement because of the smaller first cost and the possibility that maintenance dredging under this plan would not be excessive, but, if actual experience demonstrates after a few years' trial that jetty B might aid in properly maintaining the channel at reduced cost, then further consideration will be given to its construction.

The additional studies would include model tests to determine the best jetty plan with respect to the effects on tidal currents and on the amount that maintenance dredging would be reduced. In order to verify the model, prototype data on the amount of dredging required to maintain the 48-foot channel without jetty B would be essential so that comparative test could be made to estimate the amount of reduction in dredging that would be caused by construction of jetty B.

CONCLUSIONS

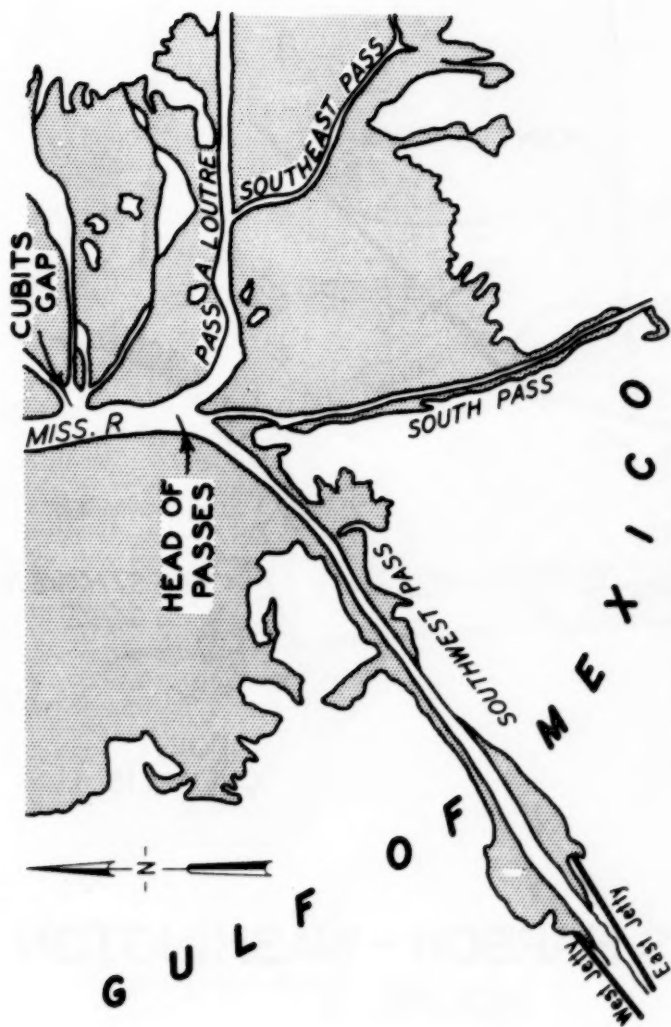
The engineering problems encountered in tidal waterway development are complex and often baffling in the varied interaction of many forces. There is as yet only a limited understanding of many aspects of tidal hydraulics, which necessitates rather heavy reliance on intuition and judgment in designing essential improvements for accommodating the constantly expanding volume of waterway traffic. The hydraulic model will continue to be a necessary and effective tool in the solution of engineering problems in tidal waterways, because it effectively integrates many of the factors and influences which, heretofore, and probably for a long time to come, have defied mathematical expression.

ACKNOWLEDGMENT

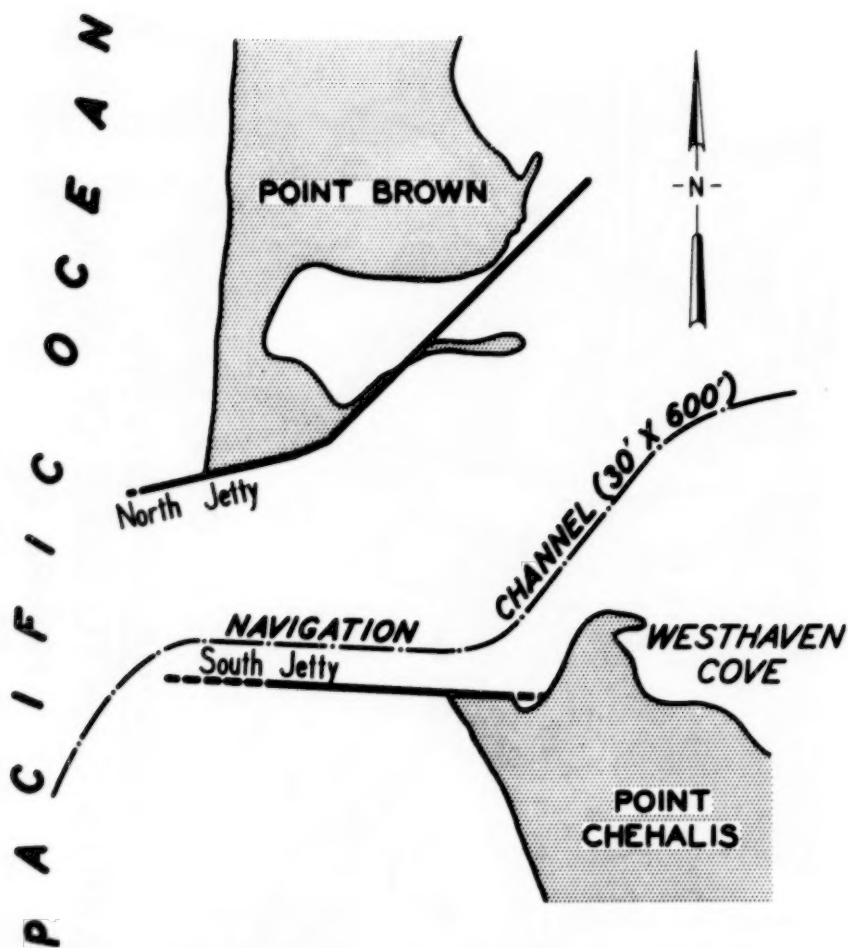
Material which appears in reports of the Committee on Tidal Hydraulics, the Engineering Manual for Civil Works, and various official reports of the Corps of Engineers pertaining to tidal waterway projects were utilized in preparing this paper.



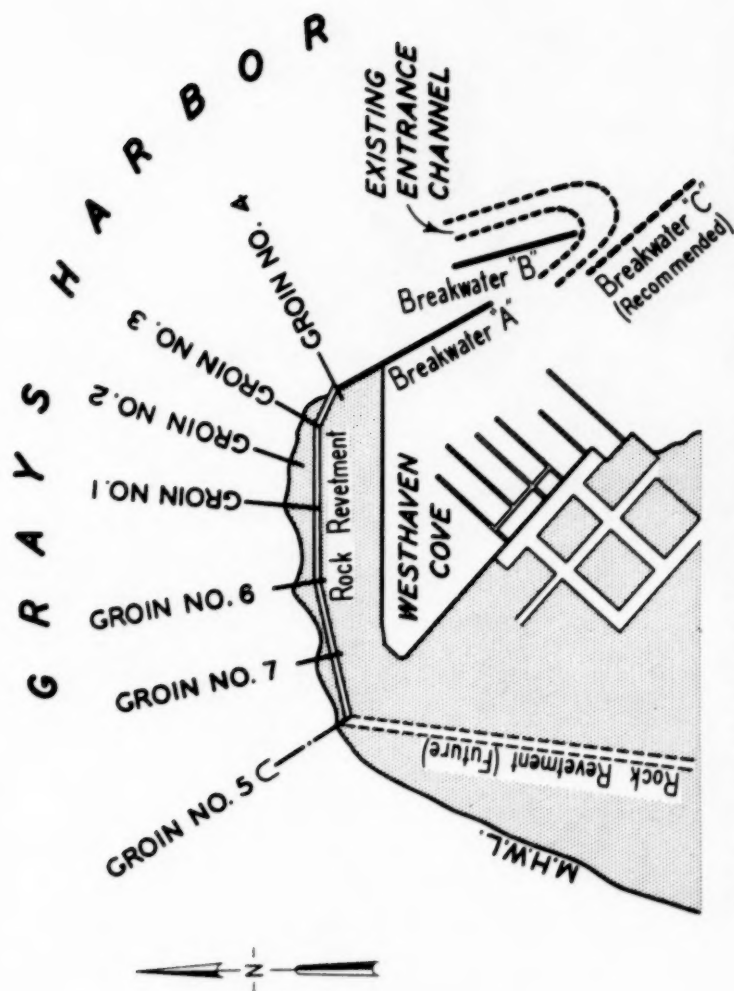
**MISSISSIPPI RIVER
NEW ORLEANS TO GULF OF MEXICO
FIGURE I**



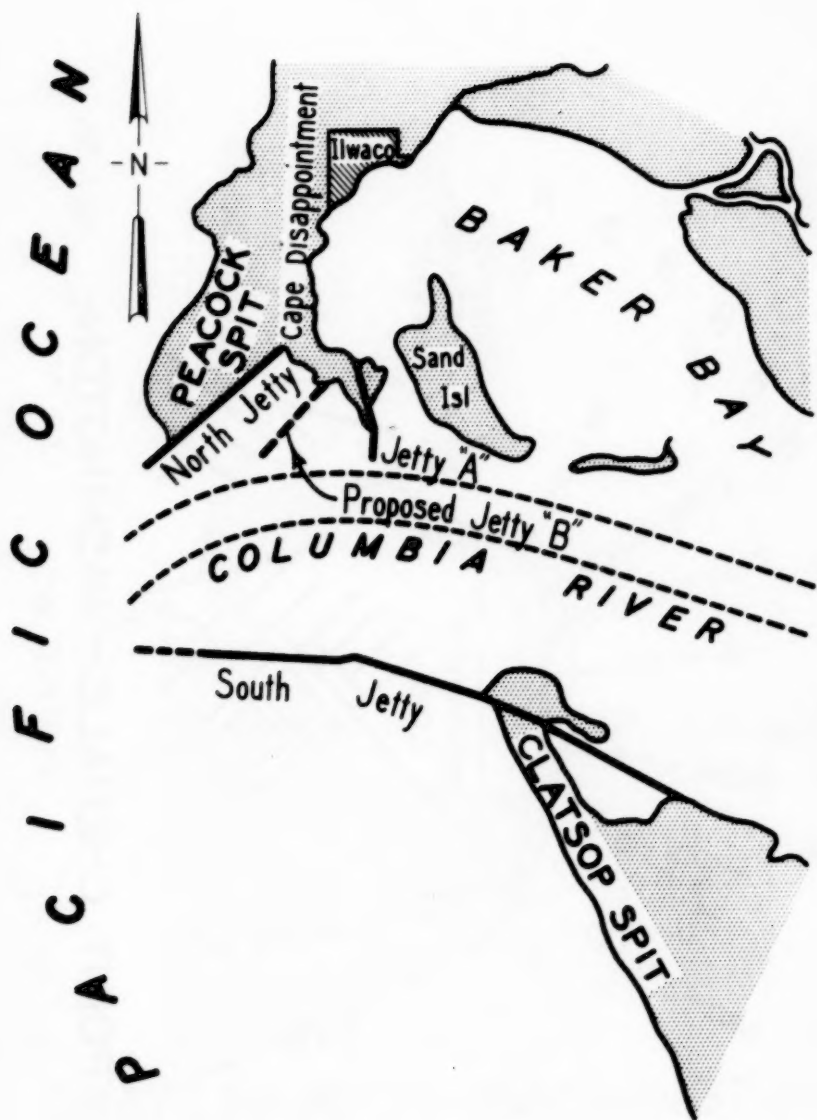
MISSISSIPPI RIVER
CUPITS GAP TO GULF OF MEXICO
FIGURE 2



GRAYS HARBOR - WASHINGTON
FIGURE 3



POINT CHEHALIS - WASHINGTON
FIGURE 4



COLUMBIA RIVER AT MOUTH
FIGURE 5